GEOTHERMAL RESOURCE POTENTIAL OF WILLCOX AREA, ARIZONA

by

James C, Witcher

Arizona Geological Survey
Open-File Report 82-4

1982

Arizona Geological Survey
416 W. Congress, Suite #100, Tucson, Arizona 85701

Funded by the U.S. Department of Energy
Contract Number DE-FC07-79ID12009

This report is preliminary and has not been edited or reviewed for conformity with Arizona Geological Survey standards

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Introduction

Willcox, Arizona, established in 1880 when the Southern Pacific Railroad was built, lies on the east edge of the Willcox Playa at the northwest base of the Dos Cabezas Mountains in the Sulphur Springs Valley of southeastern Arizona (Fig. 1). The Sulphur Springs Valley, named for no longer flowing springs at the base of low hills south of the playa, is underlain by the sediment filled Willcox basin. While sulphurous springs are frequently thermal and may indicate significant geothermal energy potential, the namesake springs in the valley are not believed to have been thermal.

However, several wells drilled for irrigation and domestic water supplies have encountered thermal water (>30°C). This report summarizes and discusses these occurrences in context to their geologic and geohydrologic settings. An additional goal of this study is to identify areas in the Willcox basin, which have geothermal resource potential. Because the Willcox area has a large agricultural economic base and has relatively cool nights in the winter, significant opportunities exist for direct use of geothermal heat. Agricultural and space heating applications best utilize lower temperature resources. Possible development of geothermal resources in the Willcox area may be advantageous in saving energy and conserving ground water. Many forms of geothermal agriculture such as greenhouses use far less ground water per acre for irrigation than conventional crops such as cotton.

Land Ownership

Figure 2 is a land ownership map of the Willcox basin. Most land in the basin is privately owned, but an important percentage of state land is interspersed. Federal land ownership and control is minimal except in the Willcox Playa where military reservation is designated. In general, the area has a legally favorable land status for geothermal development. The most evident

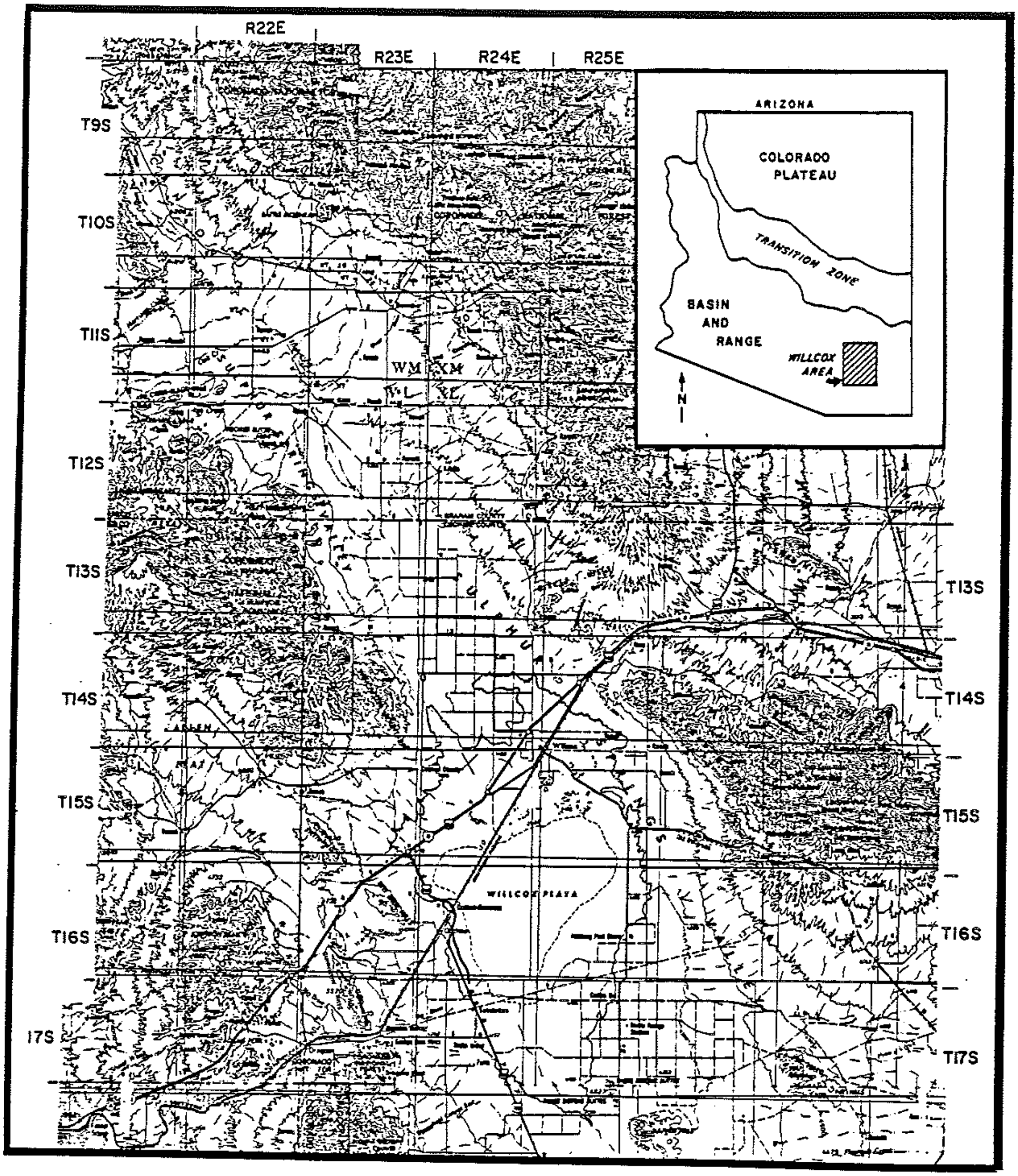


FIGURE 1. Location map of the Willcox area

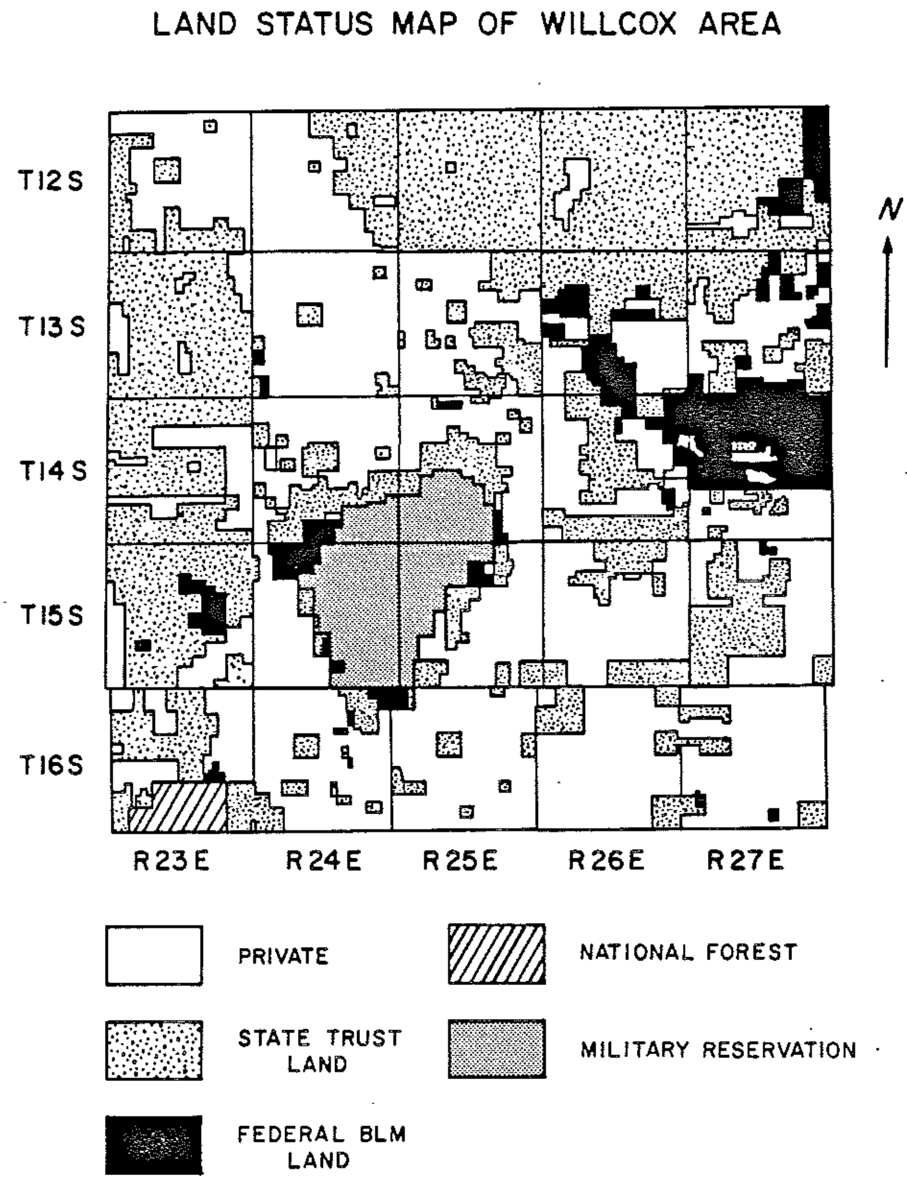


FIGURE 2. Land ownership map of the Willcox area.

exception is the military controlled land on the playa; however, practical considerations such as flooding may make the playa unsuitable for development.

Previous Studies

Several studies are published on general and specific aspects of the geology and geohydrology of the Willcox basin. A reconnaissance geologic map of the area is published in Cooper (1960). Silver (1978) summarizes the Precambrian geology of the region. Paleozoic stratigraphy of the surrounding region is detailed by Hayes (1978), Ross (1973), Ross (1978) and Gilluly and others (1954). Regional stratigraphic relationships of Mesozoic sediments and volcanic rocks in southeastern Arizona is discussed by Hayes and Drewes (1978), Bilodeau (1978), and Titley (1976). Summaries of Tertiary geology in southeastern Arizona are published by Shafiquallah and others (1978) and Scarborough and Perice (1978). Volcanic geology of the Giliuro Mountains, west of the basin, is outlined in Creasey and Krieger (1978). Recently, Thorman (1981) presented a preliminary study of the geology of the Pineleno Mountains. Geology in the Dos Cabezas and Chiricahua Mountains is discussed by Sabins (1975), Marjaniemi (1968), and Erickson (1981 and 1968). Brown and Schumann (1969) briefly outline the basin fill stratigraphy in the Willcox Basin. Geohydrologic studies and tabulations of well records in the Willcox basin are available in Brown and others (1963), Brown and Schumann (1969) and in Mann and others (1978).

Bouguer gravity data, maps and modeling interpretations are published by Peterson (1966), Aiken and Sumner (1974), Aiken (1978), Lysonski and others (1980), and Oppenheimer and Sumner (1981).

Regional Setting

The Willcox basin lies in the Mexican Highland section of the Basin and Range province in southeastern Arizona (Fig. 1). In comparison with the Sonoran section in southwestern Arizona, this area has high elevation (>4,000 feet or 1.2 km). The Willcox basin is mostly closed to external drainage; however, the Gila-San Simon River system drains a basin east of Willcox and the San Pedro River drains the basin on the west. Only the northern end of the Willcox basin has external drainage, which is provided by Aravaipa Creek, a tributary of the San Pedro River. Aravaipa Creek is beyond the area of this report.

A zone displaying relatively higher frequency of seismicity occurs in southeastern Arizona and encompasses the Willcox basin area (DuBois and others, 1982). Most areas where geothermal resources are currently being developed occur where tectonism is active or has a youthful age. To date, no Quaternary fault scarps are identified in the Willcox basin. Pleistocene fault scarps are observed in the San Simon Valley, east of Willcox, at the base of both the Pineleno and Chiricahua Mountains (Menges and others, 1982).

No Quaternary volcanic rocks are identified in the Willcox basin. Quaternary basaltic rocks occur on the San Carlos Indian Reservation in the Gila Valley and in the San Bernardino Valley, both north and south, respectively, of the Willcox basin.

Conductive heat flow studies in southern Arizona have shown a mean heat flow of 79.5 mWm^{-2} (Shearer and Reiter, 1981); while no conductive heat flow measurements are as yet published for the Willcox basin, it is reasonable to assume a 79.5 mWm^{-2} value as background heat flow for the basin. A 67 mWm^{-2} is the worldwide average heat flow.

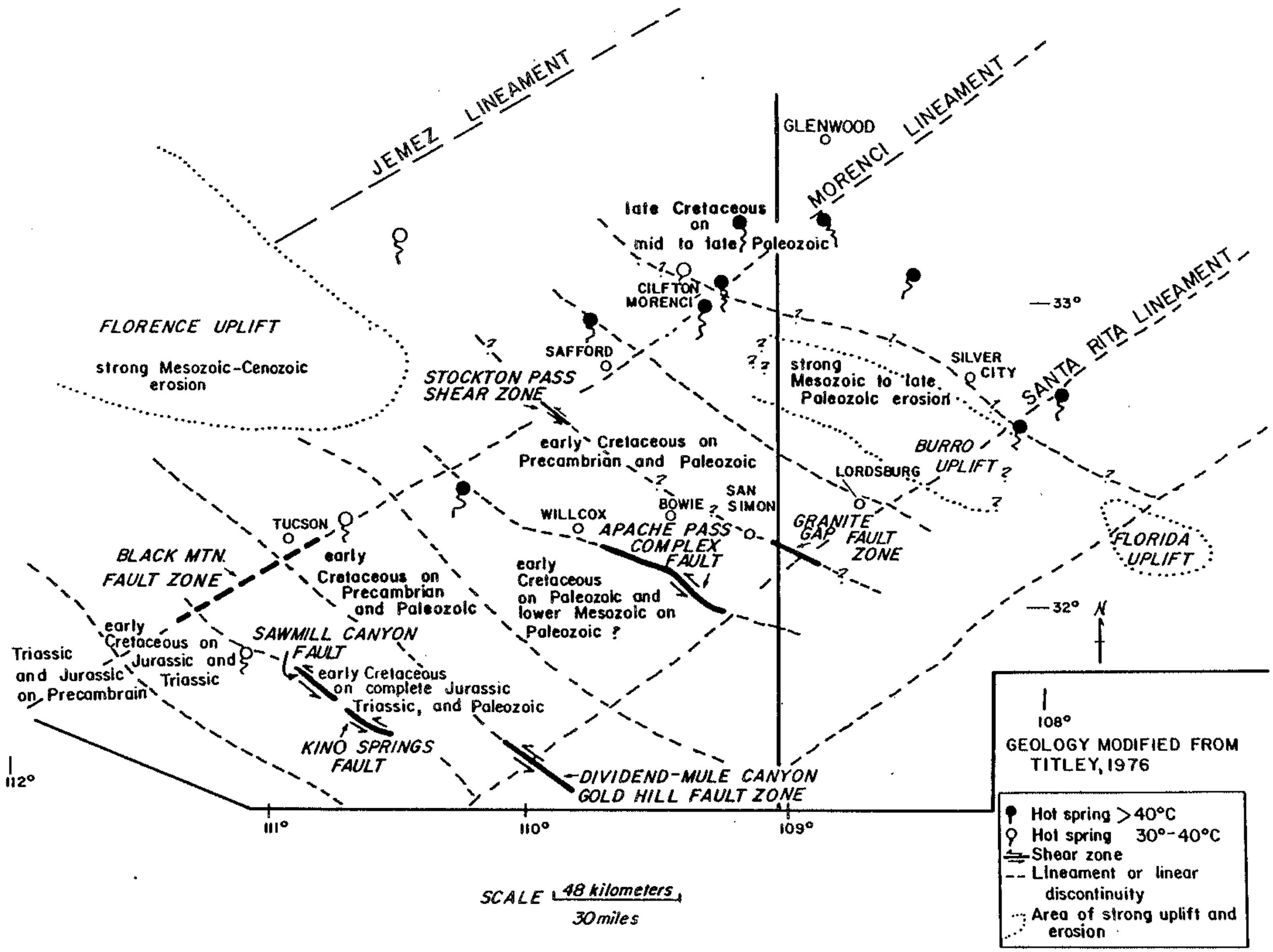


FIGURE 3. Regional lineaments and crustal discontinuities

Highly fractured rock and deep seated zones allowing magmatic intrusion or deep circulation of water is a primary feature in many geothermal systems. Linear crustal discontinuities and lineaments, which may indicate zones of highly fractured rock, are identified for evaluation and interpretation of known shallow geothermal manifestations, and exploration for deep systems.

Linear discontinuities, in the basement (pre-late Miocene rocks) and with regional extent, cross the Willcox basin in both west northwest and northeast directions (Fig. 3). The west-northwest striking discontinuities are linear zones separating terranes exhibiting unique Mesozoic stratigraphic relationships (Titley, 1976). Boundaries of linear zones, where they are exposed, reveal complex faults that have incurred repeated movement since Precambrian time (Lutton, 1958; Drewes, 1971; Drewes, 1972; Swan, 1976; Titley, 1976; and Titley, 1981). Movements on individual fault zones mapped along the linear discontinuities have included both strike-slip, normal and reverse, or thrust displacements. One of these linear discontinuities apparently divides the basement of the Willcox basin into two terranes which differ in pre-Tertiary stratigraphy. Major faults are mapped in both the Winchester and Dos Cabezas Mountains coincident with this zone (Erickson, 1968; and Drewes, 1981). Another west-northwest discontinuity at Stockton Pass in the Pineleno Mountains is discussed by Swan (1976).

The Morenci lineament, first defined by Chapin and others (1978), traverses the Willcox basin from northeast to southwest; however, no readily apparent linear features are observed in the basin. However, every thermal spring greater than 40°C in southeastern Arizona occurs within 20 km of the median of the lineament trace (Witcher, 1981). The nearby Hookers Hot Spring in the southern Galiuro Mountains is one example.

Outline of Geology

Precambrian rocks exposed in the surrounding Dos Cabezas, Pineleno, and Winchester Mountains, and in the adjacent Johnny Lyon Hills and Dragoon Mountains record major sedimentation, intensive metamorphism and plutonism. The oldest of these rocks, the Pinal Schist, comprise a thick sequence of mostly greenschist-grade, but locally-amphibolite-grade, metamorphosed sediments and volcanic strata that have been tightly folded at all scales with axial planes striking northeast (Silver, 1978). Metamorphism of the Pinal Schist was immediately followed by intrusion of the 1625my old Johnny Lyon Granodiorite (Silver, 1978). At about 1420my to 1440my large batholiths of porphyritic granite were explaced which have large (up to 4cm) potassium feldspar phenocrysts (Silver, 1978; Erickson, 1968). Examples of these plutons include the Tungsten King Granite, Oracle Granite, Polecat Quartz Monzonite and Rattlesnake Point Granite.

An extended period of erosion followed the emplacement of the 1420-1440my old granite. Upon the resulting beveled surfaces, sediments of the Apache Group were deposited. At about 1100my, sills of diabase were intruded into the Apache Group sediments (Silver, 1978). It should be noted, however, that the Apache Group sediments are probably removed by erosion because no Apache Group sediments are observed in the mountains east of the Little Dragoon Mountains.

The anisotropic nature of the crust in southeastern Arizona, which is suggested by regional discontinuities and lineaments, had an origin during Precambrian. Northeast trending fold axes and shear zones are observed in the Pinal Schist (Silver, 1978). West-northwest shear zones are devēloped in plutons of the Tungsten King Granite affinity (1420-1440my) (Swan, 1982; and Swan, 1976). Some west-northwest shear zones such as the one at Stockton Pass

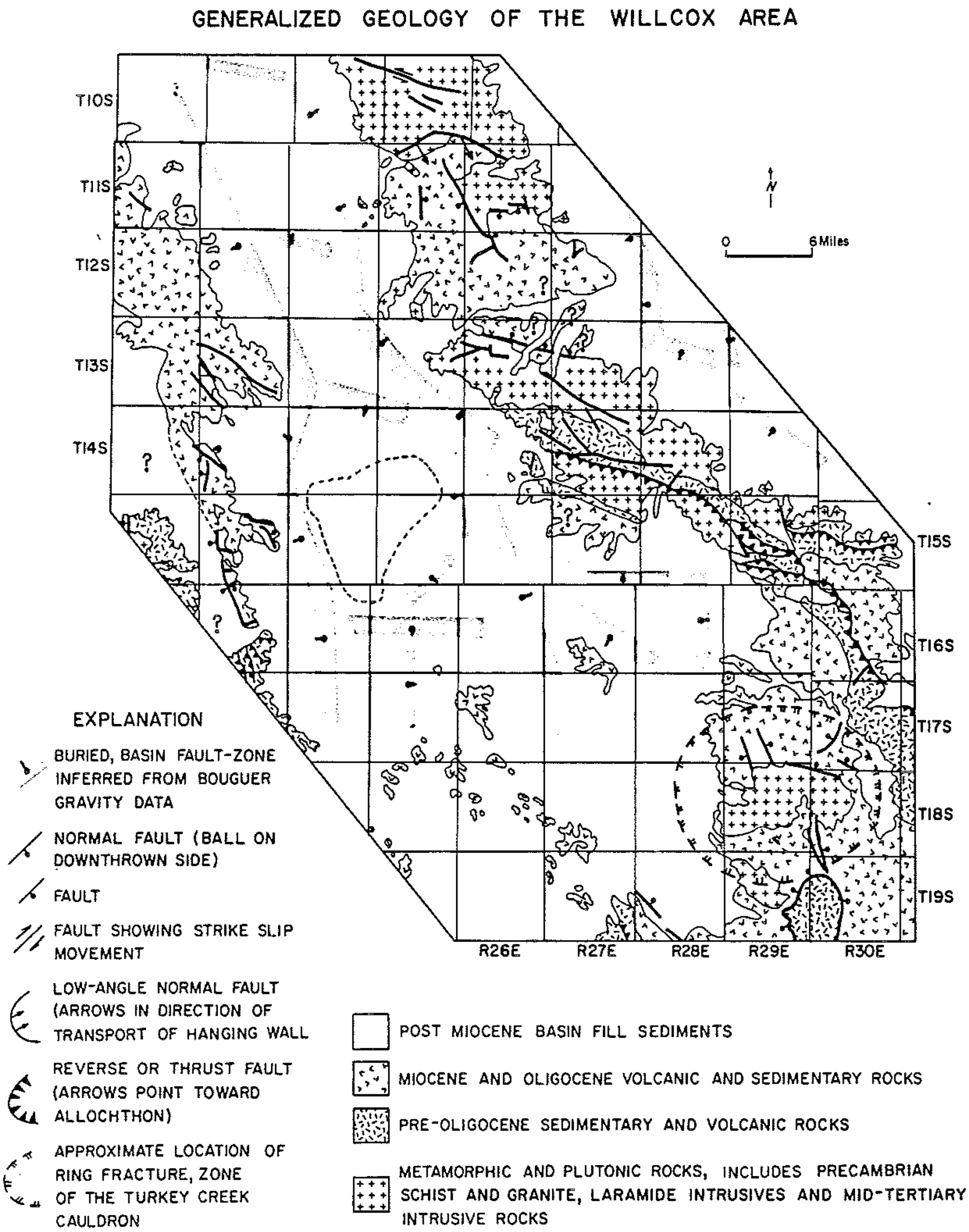


FIGURE 4. Generalized geology of the Willcox area

are intruded by Precambrian diabase and have had post-Precambrian displacement (Swan, 1976).

Where fully exposed, Paleozoic rocks unconformably overlie the Precambrian lithologies. A basal arkosic sandstone is overlain by a sequence of interbedded sandstones, shales and carbonate rocks that become increasingly carbonate rich is they go up section and younger in age. Depositional trends observed in isopach constructions and facies distribution of Paleozoic sediments reflect movement of the crust along trends consistent with the direction of structure developed in the underlying Precambrian crust. Increased relative movement of the crust during Pennsylvanian and Permian is reflected by the development of the Pedrogosa Basin, south of the Willcox basin, and by increased sand and by minor disconformities.

Mesozoic rocks in the region surrounding the Willcox basin indicate significant tectonic activity, which continued into Tertiary time. Small outcrops of Triassic to Jurassic volcanic and sedimentary rock are observed on the southwest slope of the Dos Cabezas Mountains and in the Little Dragoon Mountains (Hayes and Drewes, 1978; Drewes, 1981; and Titley, 1976). Lower Cretaceous, Bisbee Group sediments unconformably overlie the older Mesozoic volcanic and sedimentary rocks in the Dos Cabezas and Little Dragoon Mountains. However, no Cretaceous rocks are observed in the Pineleno or in the southern Galiuro Mountains. The Glance Conglomerate (base of Bisbee Group) consists of highly cemented conglomerate derived from Paleozoic strata. The fanglomerate nature and distribution of the Glance Conglomerate suggests differential uplift along older west-northwest crustal discontinuities such as the Dos Cabezas discontinuity of Titley (1976). Southwest of Apache Pass, in the Dos Cabezas Mountains, the Glance Conglomerate overlies Pennsylvanian Horquilla Limestone; while northeast of Apache

Pass, the Glance Conglomerate overlies the Ordovician to Cambrian El Paso Formation and Coronado Sandstone (Sabins, 1957). The unconformity at the base of the Glance Conglomerate has considerable relief. Also, of major interest is the apparent Mesozoic erosional thinning of the Paleozoic sequence in a north and eastward direction. Structure inferred by the Glance Conglomerate and the erosion of Paleozoic stratigraphy may indicate a southwest boundary for the Burro uplift of Elston (1958). North of the Burro uplift, which is apparently centered in the Burro Mountains of southwestern New Mexico, progressively older Paleozoic rocks are observed in outcrop as the uplift is approached. Late Cretaceous and lower Cretaceous sediments unconformably overlap both Precambrian rocks on the uplift and Paleozoic rocks on north and south, uplift margins, respectively. The Burro uplift is thus pre-Cretaceous, but probably post-mid to late Permian. That part of the Willcox basin north of the Dos Cabezas discontinuity is probably on the Burro uplift and it is unlikely that Paleozoic rocks are present. In fact, no Paleozoic or Cretaceous rocks are observed in the Pineleno Mountains. In the middle Galiuro Mountains, Tertiary volcanic rocks overlie Precambrian Oracle Granite, while in the Little Dragoon Mountains and Winchester Mountains, Tertiary volcanic rocks overlie Eocene? gravels, Cretaceous, Paleozoic and Precambrian rocks (Creasey and others, 1978; and Drewes, 1981).

At the end of the Cretaceous, a major orogeny disrupted the crust of southern Arizona. This event, the Laramide orogeny, 80 my to 40 my, involved uplift, volcanism, intense compressive deformation and plutonism (Coney, 1978; and Shafiqullah and others, 1980). During this time Arizona's important porphyry copper deposits were emplaced.

East of Willcox, in the Dos Cabezas Mountains, Laramide plutonism is well exposed. Erickson (1968) describes a large (15 km^2) intrusive breccia which forms the two peaks that give the range its name. The breccia intrudes folded and deformed Bisbee Group (early Cretaceous) and the west-northwest trending Apache Pass fault zone. The Silver Camp quartz diorite stock (64 my) intrudes the breccia (Erickson, 1981). Thus, both the breccia and the stock are Laramide age and indicate significant magmatic activity along the Dos Cabezas discontinuity.

Compressional tectonism in the Dos Cabezas and Chiricahua Mountains is evidenced by two structural terranes (Sabins, 1957; and Drewes 1976, 1980, and 1981). The northern terrane appears in situ or autochthonous. The other terrane is allochthonous and is thrust over the northern autochthon. The allochthonous block, formed by the Fort Bowie and Wood Mountain thrust faults, is correlated on a regional scale by Drewes (1976) as part of an extensive crustal sheet which is thrust northward and northeastward in southeast Arizona and southwest New Mexico. However, it should be noted that other explanations are proposed for the thrust faults in southeastern Arizona, which do not require the extensive horizontal movement of the crust that is implied by Drewes (1976). Jones (1963), Davis (1979), and Keith and Barrett (1976) present arguments which support basement cored uplift accompanied by local thrusting.

A renewed phase of volcanism began during mid-Tertiary in the Willcox basin region after an apparent lull in volcanism during Eocene. In the Chiricahua Mountains, the mid-Tertiary volcanism culminated in the eruption of several, extensive, welded, ash flow tuff flows. These flows, comprising the Rhyolite Canyon Formation (25 my), originated from the resurgent Turkey Creek caldera centered in the Chiricahua Mountains (Marjaniemi, 1968; Shafiquallah and other, 1978; and Latta, 1982). A major unconformity separates the Rhyolite Canyon Formation from the underlying Faraway Ranch and Nipper Formations, which are inturn, each, separated by an unconformity. Bedding dip in the Faraway Ranch Formation (~28 – 29 my) and the Nipper Formation (~32 my) dip 20 to 40 degrees, respectively (Shafiquallah and others, 1978; and Sabins, 1957). The Faraway Ranch Formation appears to thicken toward the south in conformance with bedding dip and may have a southerly source area. Significant subsidence or down warping is indicated after both eruption of the Nipper Formation and the Faraway Ranch Formation lavas, and tuffs.

In the Galiuro Mountains, Winchester Mountains and Little Dragoon Mountains, a sequence of mid-Tertiary volcanic rocks is subdivided into two parts separated by a major erosional unconformity (Creasey and Krieger, 1978). The lower section consists of andesite to rhyodacite, which is capped locally by a "turkey track" andesite flow (Creasey and Krieger, 1978). An erosional unconformity with up to 300 m of relief separates the 29 to 26 my andesite to rhyodacite unit from the younger, overlying, ash flow tuff unit (Creasey and Krieger, 1978). The ash flow tuff unit has intercalated, andesite flows and has several conglomerate strata whose clasts were derived from Precambrian, Paleozoic and underlying andesite-rhyodacite flows (Creasey and Krieger, 1978). The conglomerate derived from pre-Tertiary rocks may indicate relative subsidence or downwarping in the Galiuro Mountains area during early Miocene.

Thorman (1981) discusses the Tertiary geology of the southern Pineleno Mountains. During Oligocene the granite of Gillespie Mountain (~36 my) was intruded into Precambrian rock; but it is in low-angle fault contact with overlying and younger Miocene volcanic rocks (Swan, 1976 and Thorman, 1981). The Miocene volcanic rocks are interpreted by Thorman (1981) as remanents of a complex eruptive center (27 to 23 my) which began with andesitic flows and culminated in felsic flows, tuffs and a dome. Considerable relief is indicated by gravels comprised of Precambrian clasts deposited in channels between the two oldest andesite flow units (Thorman, 1981). The upper flow unit resembles a "turkey track" andesite (Thorman, 1981).

A potentially important Tertiary structural feature in the southern Pineleno Mountains is the normal, low-angle, oblique-slip, Oak Draw fault. This fault, having a crush and gouge zone up to 10m thick, separates the Miocene volcanic rocks from the Oligocene Gillespie Mountain stock and Precambrian rocks. Also, gravels overlying the fault contain no Oligocene granite clasts (Thorman, 1981). Quartz latite dikes (23my) are cut by the Oak Draw fault. Similarly, a low angle fault in the Eagle Pass area on the northwest end of the Pineleno Mountains cuts 24 to 25my dikes (Blacet and Miller, 1978; and Shafiqullah and others, 1980) and displaces steeply dipping Tertiary gravels into contact with Precambrian rocks.

Davis (1980) and Thorman (1981) suggest that these low angle faults are an element of a metamorphic core complex in the Pineleno Mountains. Studies of metamorphic complexes such as the Rincon-Catalina-Tortolita metamorphic core complex indicate they evolved during and closely following mid-Tertiary volcanism as a result of regional tectonic strain, thermal pertubation, and tectonic denudation (Davis and Coney, 1979). A four element morphology characterizes most studied metamorphic core complexes (Davis and Coney, 1979, and Davis, 1980). In general, a mylonitic augen gneiss core is overplated by a metamorphic carapace of highly stretched greenschist to amphibolite grade metamorphic rocks derived predominantly from younger Precambrian, Paleozoic and Mesozoic strata. The metamorphic rocks are separated from unmetamorphised but highly deformed Precambrian to early Miocene "cover rocks" by a low-angle fault zone formed of mylonite and mylonite breccia (Davis, 1980). The low-angle Eagle Pass and Oak Draw faults may represent a metamorphic core complex structural element. A possible metamorphic carapace is observed only on the northeast face of the Pineleno Mountains.

Fractured Tertiary volcanic and sedimentary "cover rocks" may underlie the northern Willcox basin at depth. Such cover rocks and a low-angle fault zone may act as a geothermal reservoir where they are present and are hydrologically connected to deeply circulating water flows.

Metamorphic core complex arching, tectonic denudation, and erosional unroofing is frequently recorded in moderately to slightly deformed, mostly well cemented clastic sediments. The Pantano and Rillito beds at the base of the Rincon-Catalina Mountains in the Tucson basin are examples. These rocks are faulted by listric-normal faults characteristic of thin-skinned extension. Deformed Tertiary sediments mapped by Cooper (1960) east and northeast of Willcox may fit the Rillito-Pantano tectonic and depositional environment.

Present day basins and ranges began to develop during middle to late Miocene (15 to 10my), as the crust cooled after mid-Tertiary thermal disturbance and low angle near surface extension (listric normal faulting) was replaced by high-angle-normal faulting characteristic of crustal rifting (Scarborough and Peirce, 1978). Scarborough and Peirce (1978) name this tectonism the "Basin and Range disturbance". During this tectonism the crust of southern Arizona broke into a zig-zag pattern of horsts (mountains) and grabens (basins). Valleys of southern Arizona roughly coincide with structural basins; however, the valleys are more extensive due to erosion of the horsts which have created pediments that laterally extend the low lying topography.

Modeling of Bouguer gravity data for the Willcox basin indicates up to 2.5 km of sediment fill (low density rock) (Aiken, 1978).

Sediments filling the Willcox basin are poorly understood. Brown and Schumann (1969) break the stratigraphy into two major subdivisions: consolidated alluvium and unconsolidated alluvium. The consolidated alluvium of Brown and Schumann (1969) is probably not basin fill sediment. The deformed nature of these sediments indicates they are apparently pre-Basin and Range disturbance and are probably Rillito or Pantano equivalent sediments. Brown and Schumann (1969) place an unconformity between the consolidated and unconsolidated sediments. While this relationship is easily seen in the area north and east of the Circle I Hills, the division is not clear from drillers logs of wells drilled in the basin. No attempt is made in this report to use driller's logs to distinguish the consolidated and unconsolidated sediments in wells because deformation or bedding attitude cannot be observed; and deeply situated basin fill sediments may be cemented.

The unconsolidated sediments of Brown and Schumann (1969) are broken out into two facies. The lake-bed facies (clay and silt) is underlain and overlain by an alluvial facies (sand and conglomerate). The clay and silt beds (lake-bed facies) provide a very important geologic setting for the occurrence of low temperature (<100°C) geothermal resources. These fine grained sediments are characterized by low thermal conductivities which can cause high temperature gradients even with normal crustal heat flow. Because clay and silt are relatively impermeable, they act as aquacludes and confine aquifers of sand and conglomerate. This prevents significant convective heat loss. Thermal water in this geohydrologic setting is the result of a conductive thermal regime.

Geothermal Resources

Introduction

The only previous study of geothermal resources specifically pertaining to the Willcox basin was highly reconnaissance in scope (Jones, 1979). The present study is a more rigorous evaluation of well temperature and chemistry data, geology and geohydrology information in the Willcox basin.

Thermal Wells

Low temperature geothermal resources are indicated in the Willcox basin by the occurrence of several thermal wells (>30°C) Table 1 and Fig. 5). Several of these wells encountered thermal water under artesian pressure. Thermal wells are widely scattered throughout the basin suggesting either several discrete resources or a large, extensive, thermal aquifer. Temperatures range between 54 to 30°C from wells ranging between 200 and 1,000 m depth.

Chemical quality of thermal water is variable and ranges between approximately 200 and 1,500 milligrams per liter (mg/l) total dissolved solids TDS) (Table 2). In general, but not always, the higher temperature waters from deeper wells have lower TDS. Compositions range from sodium sulfate-bicarbonate water to sodium bicarbonate-chloride water (Fig. 6). Fluoride content of the thermal waters is high and ranges from 2.6 mg/l to over 20 mg/l. Magnesium concentrations are very low in all the thermal waters.

Thermal Regime and Geohydrology

Geothermal convection systems may make their presence known by anomalous temperature wells. Such wells would have high estimated temperature gradients. Average temperature gradients for wells are easily calculated using bottom-hole temperature and well depth. In this study, the surface discharge temperature is assumed to roughly represent bottom-hole temperature. When

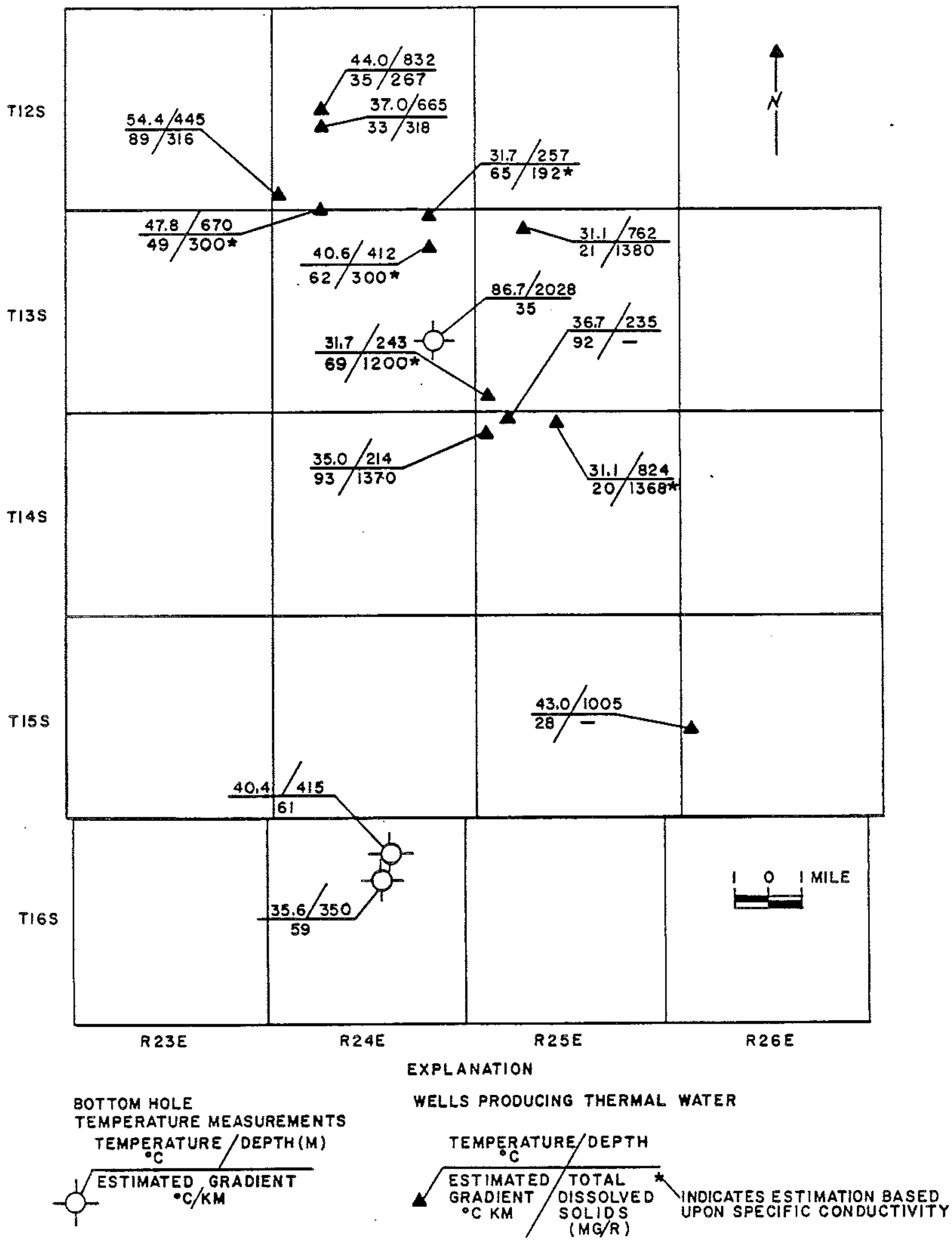


FIGURE 5. Location map of thermal wells in the Willcox area

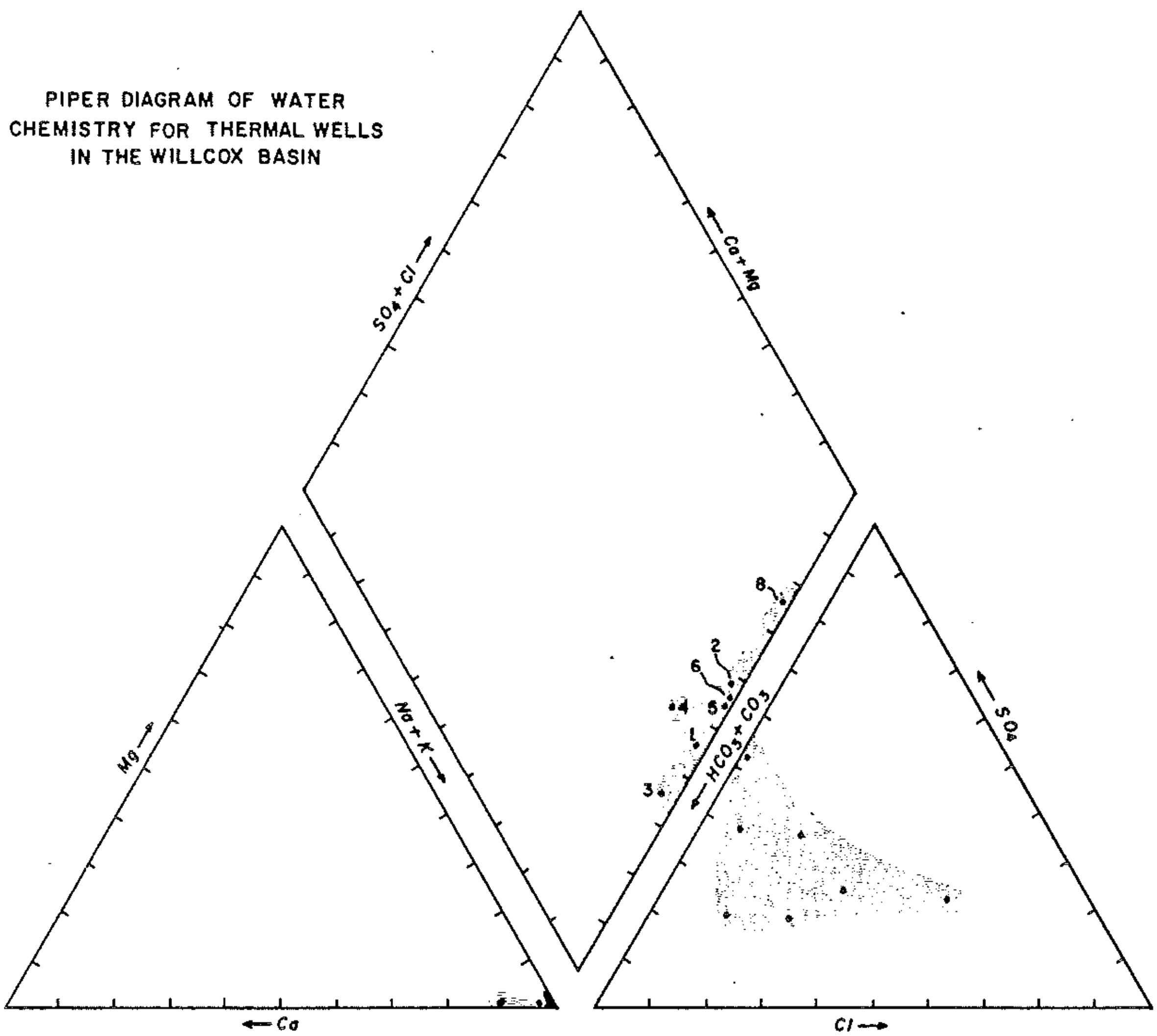


FIGURE 6. Piper diagram of thermal well chemistry

calculating a gradient the mean annual temperature (MAT) is subtracted from the well temperature, the difference in degrees celsius (^{o}C) is divided by well depth in meters (m) and the quotient is multiplied by 1,000. The calculated temperature gradient is in degrees celsius per kilometer ($^{o}C/km$).

Figure 7 compares calculated temperature gradients in the Willcox basin with respective well depths. Wells greater than 230 m depth have gradients mostly between 20 and $45^{o}C/km$. These gradients are considered background for the Willcox basin. Variation of gradients is believed due to uncertainties in depth of water entry into the wells and possibly rock thermal conductivity changes.

In wells less than 230 m depth, calculated temperature gradients range from 25 to over $300^{o}C/km$. The systematically higher gradients with decreasing depth result from ground-water movement. The temperature gradient change is approximated by the following relation:

Equation (1)

$$\frac{\partial T}{\partial z} = \frac{T - T_{mat}}{z} \times 1000$$

where: $\frac{\partial T}{\partial z}$ - temperature gradient $^{o}C/km$

T - well temperature (assumed as bottom-hole) ^{o}C

T_{mat} - mean annual air temperature (MAT) ^{o}C

z - depth (m)

Computed temperature gradient versus depth curves using equation 1 are shown in Figure 7 for well temperatures of $18^{o}C$, $22.4^{o}C$, and $30^{o}C$, respectively. The mean temperature for wells in the Willcox basin is about $22.4^{o}C$.

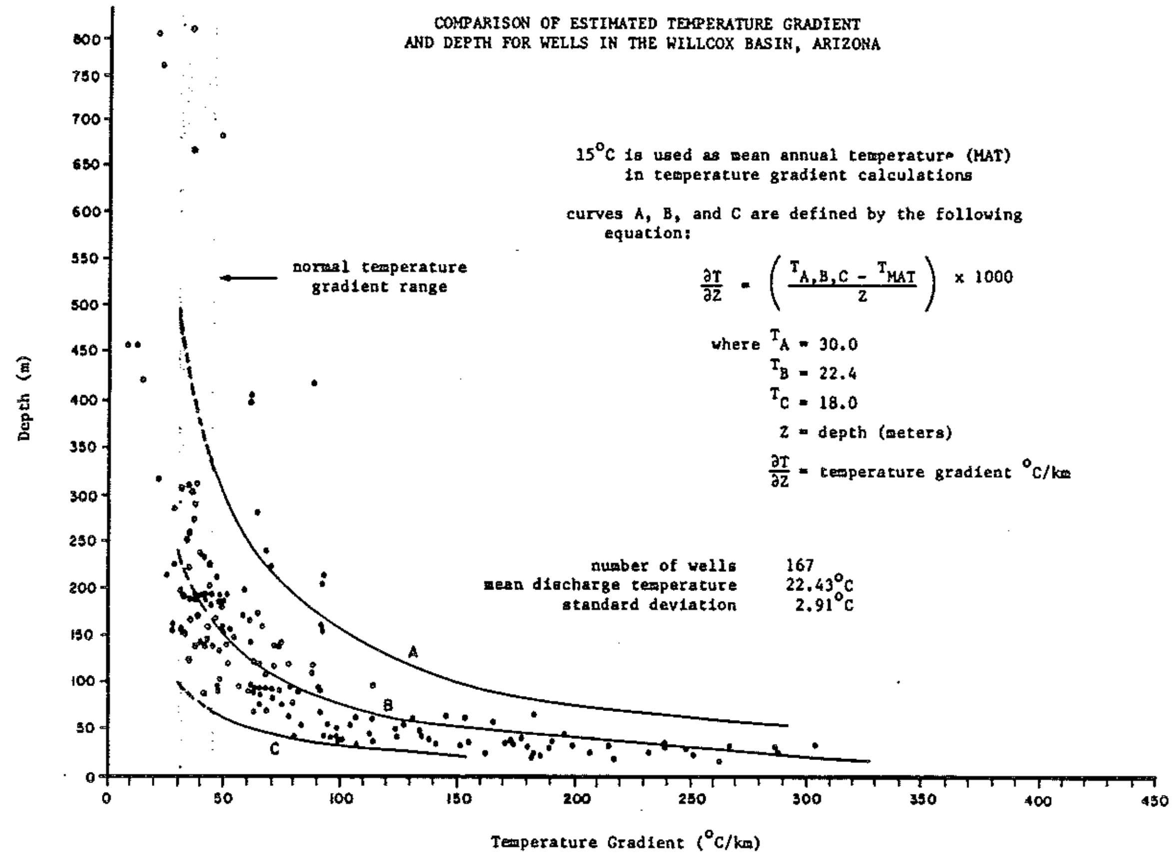


FIGURE 7. Temperature gradient versus depth of water

Calculated temperature gradients plotting on or right of Line B are interpreted in this study as caused by one or combination of three processes, or models all of which involve heat transfer by water toward the surface. In the first model, systematically increasing gradients in wells of similar depth are caused by a land surface and water table convergence in the direction of lateral water flow in shallow (<230 m) and discrete aquifers, whose temperatures change vertically with depth (above 22.4°C) (Fig. 8). The second model (Fig. 8) models the upper 230 m of the Willcox basin as a continuous aquifer whose temperature from top to bottom varies only slightly from 22.4°C as a result of rapid ground-water flow, induced by either pumping or a sloping water table in an aquifer that has high hydraulic conductivities. With the second process, estimated gradients increase systematically with decreasing well depth. A third, but important, mechanism is probably superposed on the two preceding and primary conditions. In the third category, leakage of thermal water into shallow (<230 m) aquifers from underlying confined aquifers or localized high influx of heat may cause temperatures in shallow aquifers to exceed 22.4°C.

Geothermal exploration in the Willcox basin is aided when using the above models. Wells with residual gradients which exceed line B are plotted on maps to show possible anomalies. The residual gradient is a relative measure of the degree of abnormality in the temperature gradient with models 1 and 2. This residual gradient is calculated by substracting the estimated well gradient from the gradient predicted by equation 1 for line B at 22.4°C and the specified well depth. Figure 8 shows areas where residual gradients, computed in this manner, are consistently either positive or negative. A 1975 water-table, elevation-contour map is included for comparison. In general, water-table highs and ridges correlate with negative residual gradients.

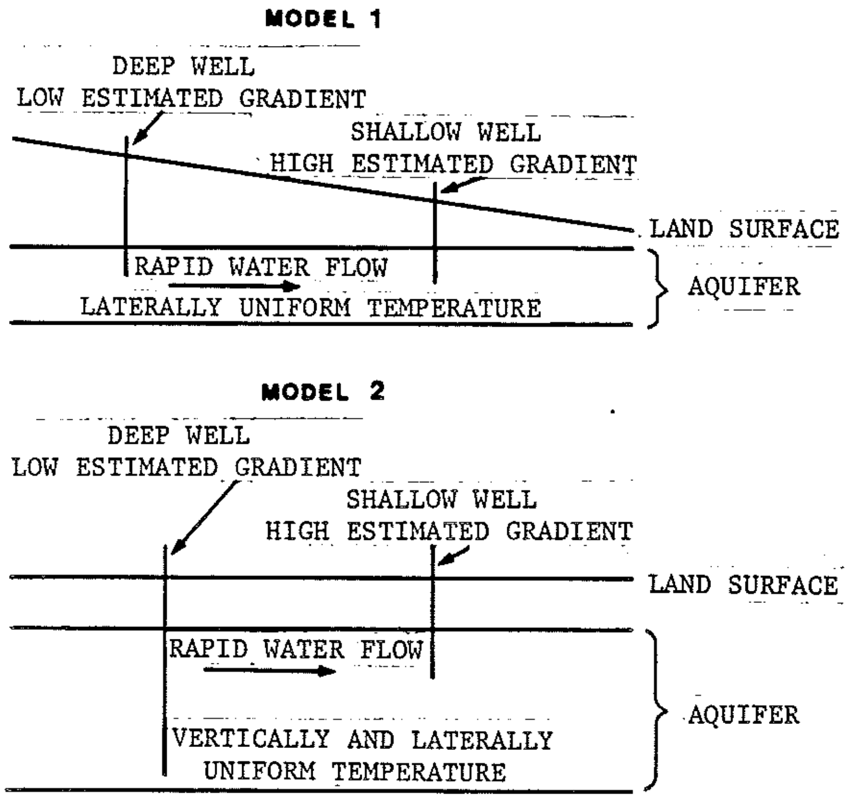


FIGURE 8. Ground-water flow and temperature models used to explain temperature.

This may indicate areas where ground water has a downward component of flow (recharge or ground-water flow into water-table depressions) or areas with a preponderance of shallow wells tapping aquifers with temperatures less than 22.4°C. Positive residual gradients generally occur in ground-water depressions. Induced upward leakage of water from deep semi-confined aquifers by heavy pumping of shallow aquifers is postulated as the cause for positive residual gradients within ground-water depressions. However, three exceptions to the above generalizations are noted. These anomalies lie near or north of Willcox. They are shown with cross hatching and labeled I, II, III, respectively in Figure 9. These areas, which have positive residual gradients, overlie water-table highs or ridges. Thermal wells (>200 m) with the high estimated temperature gradients (>60°C/km) occur in areas I, II, and III. These areas may overlie deep hydrothermal convection systems. Overlying aquifers are abnormally warm either from upward leakage of thermal water or from high heat flux due to an underlying geothermal system.

Calculated gradients of thermal wells in areas outside areas I, II, and III are normal (<45°C/km). A conductive thermal regime is indicated by those wells.

Geohydrology

Prior to large-scale withdrawal of ground water from the Willcox basin, ground-water flow was from the recharge areas on the perimeter of the basin toward the Willcox playa where discharge occurred through evapotranspiration (Brown and Schumann, 1969). Today, ground-water movement is toward water-table depressions, resulting from extensive ground-water pumping.

Figures 10a and 10b are cross-sections of subsurface stratigraphy constructed from driller's logs, location of the cross-sections is shown in Figure 11. Zones of thermal water, as noted in drillers logs, occur below

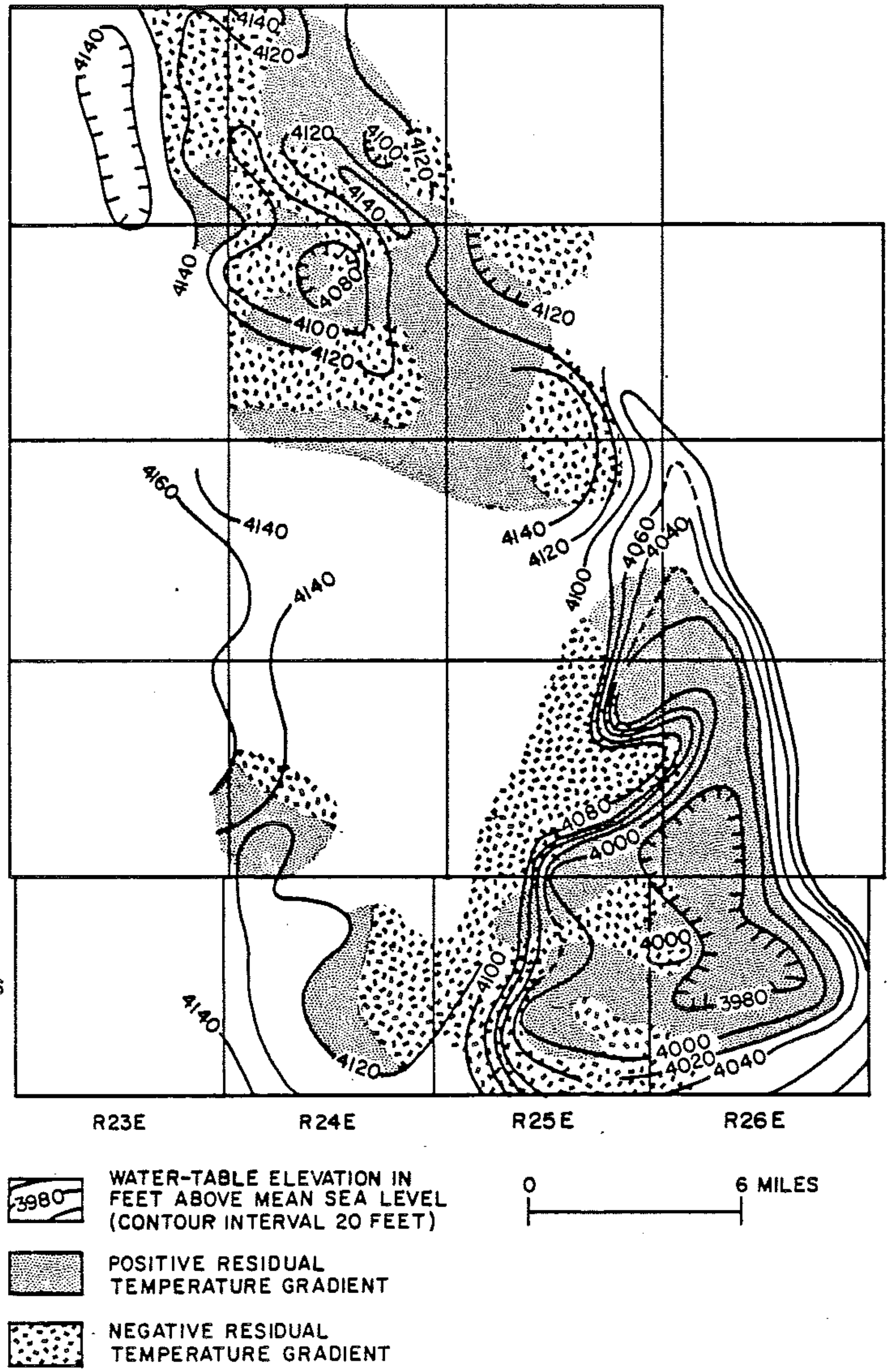
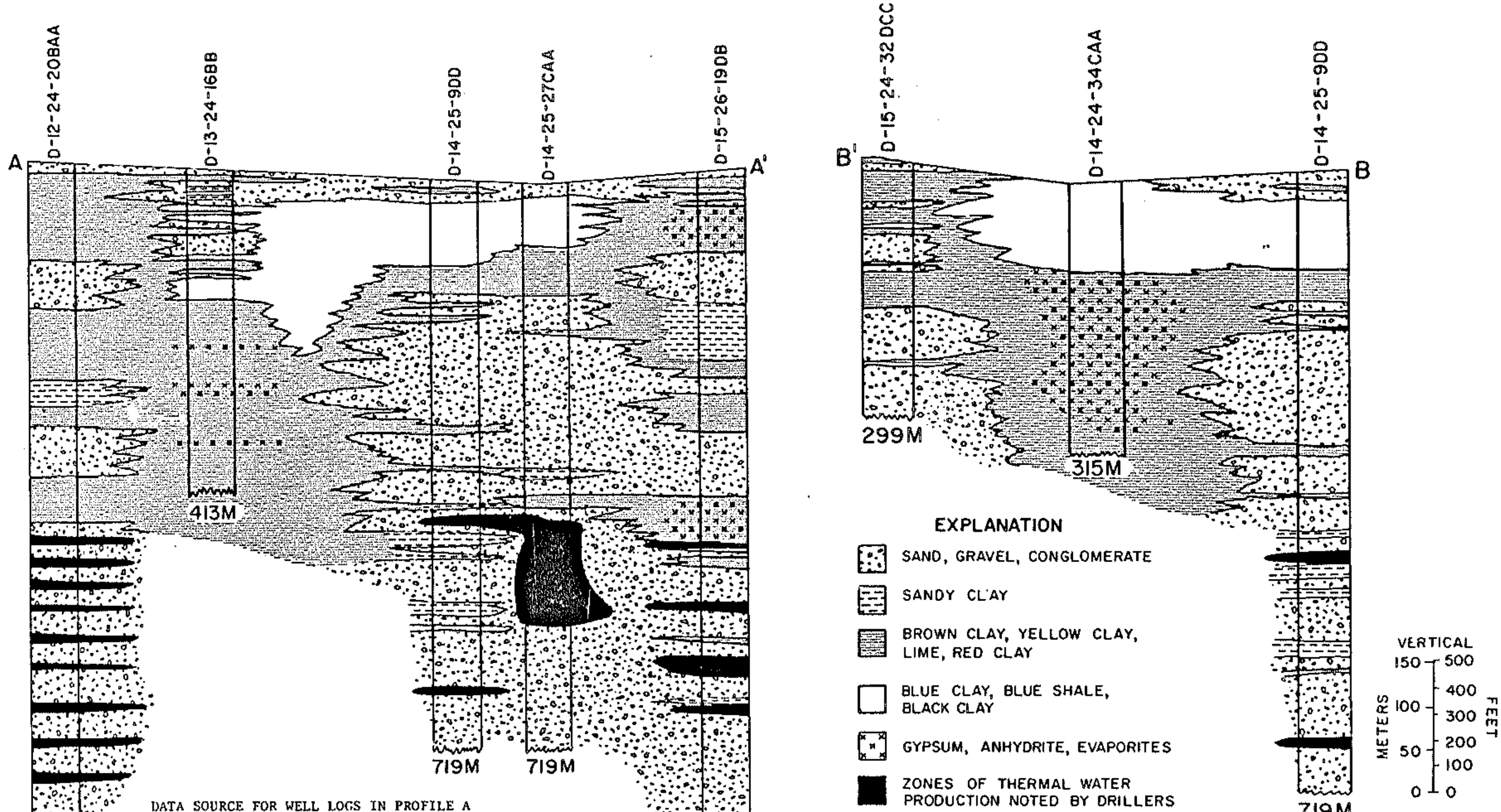


FIGURE 9. Water table map of the Willcox area with residual gradients



DATA SOURCE FOR WELL LOGS IN PROFILE A

WELL	SOURCE
D-12-24-20-BAA	BROWN AND OTHERS (1963)
D-13-24-16BBB	COATES (1952)
D-14-25-9DD	COATES (1952)
D-14-25-27CAA	BROWN AND OTHERS (1963)
D-15-26-19DB	COATES (1952)

DATA SOURCE FOR WELL LOGS IN PROFILE B

WELL	SOURCE
D-15-24-32DCC	AEPCO (SEE TABLE 4)
D-14-24-34-CAA	VINE AND OTHERS (1979)
D-14-25-9DD	COATES (1952)

FIGURE 10. Stratigraphic cross sections of the Willcox Basin

LOCATION OF STRATIGRAPHIC CROSSECTION PROFILES
IN THE WILLCOX BASIN

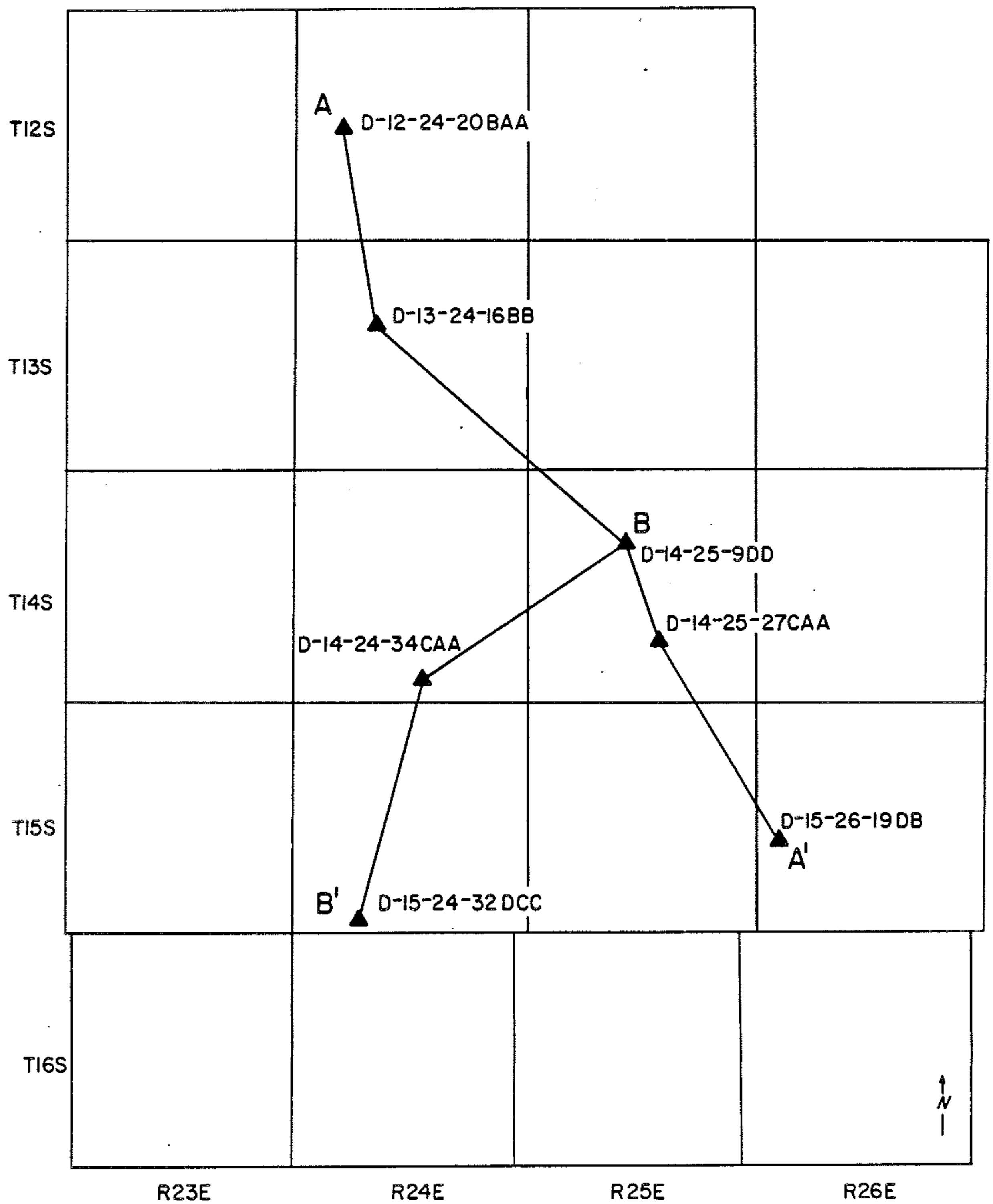


FIGURE 11. Location map of crossections

clay and silt beds in moderately indurated conglomerate and sand at 500 m (1,500 feet) depth. A widespread low-temperature resource 35 to 50°C apparently occurs between 500 m and 700 m in the Willcox basin. The aquifers containing thermal water are confined to semi-confined as indicated by artesian flow from a few wells. Thermal aquifers may exist at greater depth (>700 m) and have higher temperatures (>50°C) beneath the depositional centers for the clay and silt (lake bed facies of Brown and Shumann (1968). These areas are untested.

Geothermometry

Because many natural water-rock chemical interactions are largely dependent upon temperature, chemical geothermometry, using thermal well and spring chemistry, is often used to determine geothermal potential or predict geothermal reservoir temperatures. The technique is useful since many thermal waters represent leakage of cooled geothermal water which retains a chemical-temperature signature after exiting the geothermal reservoir.

Silica and Na-K-Ca geothermometers (Fournier and Rowe, 1966) and Fournier and Truesdell, 1973) are computed for wells with more complete chemical information (Table 3). These geothermometers are used assuming conditions, listed by Fournier, White and Truesdell (1974), governing their use and interpretation.

Analyzed silica concentrations were corrected for non-temperature dependent ionization because, at high pH, dissolved silica, $(Si(OH)_4$, dissociates to form $SiO(OH)_3^-$. Thermal waters from these wells are all saturated with respect to quartz.

The Na-K-Ca geothermometers for thermal wells 1, 2, and 3 are within 5 to 12°C of temperatures predicted by the chalcedony geothermometer. Subsurface reservoir temperatures averaging 58 to 65°C are predicted for these areas. Surface discharge temperatures range from 37 to 54.4°C. Discrepancy in the geothermometers and measured temperatures in wells 1 and 2 is puzzling because these wells are in an apparent conductive thermal regime. Well 3, which occurs over a probable hydrothermal convective system (anomalous area I), as indicated by a high estimated gradient, shows an average geothermometer temperature of 65°C.

Well number 8 has a Na-K-Ca geothermometer of 104°C, which is probably not real due to possible non-temperature dependent solution of evaporite minerals in basin fill. Well 8 is a sodium-chloride rich water and has much higher dissolved solids than wells 1, 2, and 3.

CONCLUSION. A large and extensive low-temperature geothermal resource occurs in the Willcox basin at 500 to 700 m depths. The thermal water is confined to semi-confined and is contained in moderately cemented gravel below silt and clay beds. Artesian flow at the surface may occur in some areas. Excellent water quality is indicated except for locally high fluoride concentrations and near the playa where TDS may exceed 2,000 mg/L.

Three areas adjacent to and north of Willcox have potential for thermal water with temperatures over 50°C. These areas have anomalous temperature gradients. Geothermometry predicts 60 to 65°C reservoir temperatures.

The basin is untested for conductive-gradient type resources at depths greater than 1 km. Thermal water about 100°C may exist at 2.5 km depths. However, economics and risk factors may preclude deep exploration and development in the Willcox area.

Table 1. List of thermal wells in the Willcox area

Well	Location	Depth (meters)	Temperature	Data Source
1	D-12-24-20 BAA	832	44.0	4
2	D-12-24-20 CAA	664.5	37.0	4
3	D-12-24-31 CB	445	54.4	3,4
4	D-13-24-2 BAA(2)	257	31.7	2,3
5	D-13-24-5 BA	670	47.8	3
6	D-13-24-11 ABB	412	40.6	3,5
7	D-13-25-5	762	31.1	1
8	D-13-25-31 CAB(2)	243	31.7	1,2
9	D-14-25-4 BAC	824	31.1	2,6
10	D-14-25-6 AAD	235	36.7	6
11	D-14-25-6 CBD	214	35.0	1,2
12	D-15-26-19 BBC	1005	43.0	1,6

Data Sources:

1. Brown and others (1963)
2. U.S. Geological Survey
3. Dutt and McCreary (1970)
4. Arizona Bureau of Geology and Mineral Technology
5. Arizona State Land Department
6. Peirce and Scurlock (1972)

Table 2 Chemical Analysis of Thermal Water in the Willcox Basin

Results in Milligrams per liter (mg/L)

Temperatures in Degrees Celsius

* TDS is calculated from specific conductivity using a0.6 conversion factor

Data Sources:
1. Brown and others (1963)
2. U.S. Geological Survey
3. Dutt and McCreary (1970)
4. Arizona Bureau of Geology and Mineral Technology

Table 2. Chemistry of thermal water in the Willcox area

Number	Sample	Location	Temperature	TDS	pH	Na	Na+K	K	Ca	Mg	Cl	SO_4	HCO_3+CO_3	SiO_2	Li	B	F	Date	Data Source
1	6037	D-12-24-20 BAA	44.0	267	9.3	97		0.66	2.0	0.38	24	22	88	73.8	0.032	0.15	3.2	8/81	4
2	6038	D-12-24-20 CAA	37.0	318	9.1	79		0.68	1.9	0.40	27	30	68.3	70.8	0.042	0.14	3.1	8/81	4
3	100	D-12-24-31 CB	54.4	316	9.1	47		0.7	<1	<0.1	16	30	136	65.0	0.06	<0.10	20.3	7/79	4
4	8095	D-13-24-2 BAA	31.7	320*	8.8	80		1.5	8	0	10	60	115	—	0.002	0.04	5.0	7/66	2,3
5	8100	D-13-24-5 BA	47.8	500*	9.3	138		2.0	2.0	0	2	110	127	—	0.001	0.09	18.0	7/66	3
6	8115	D-13-24-11 ABB	40.6	500*	9.4	106		1.0	0	0	24	60	98	—	0.002	0.62	10.0	7/66	3
7	—	D-13-25-5	31.1	1380	—		502		7.0	2.8	360	262	302	46	—	—	12.0	6/50	1
8	8609	D-13-25-31 CAB (2)	31.7	2000*	8.7	428		5.5	3	0	344	200	298	17	0.219	0.44	2.6	5/67	3
9	4817	D-14-25-4 BAC	31.1	2280*	—	—		—	6.9	2.7	—	—	302	46	—	—	—	—	2
11	—	D-14-25-6 CBD	35.0	1370	—		516		80	3.7	430	238	336	—	—	—	9.9	5/42	1

Table 3. Geothermometers of thermal water in the Willcox area

Well	Measured Temperature (°C)	pH Corrected Silica (mg/L)	Estimated Gradient (°C/km)	Silica Geothermometer (°C) Quartz	Chalcedony	Cristobalite	Na-K-Ca Geothermometer (°C)
1	44.0	34.8	35	86	55	26	60
2	37.0	49.8	33	102	72	51	60
3	54.4	39.0	89	91	60	41	69
8	31.7	15.2	69	54	21	5	104

TABLE 4. Driller's log of well D-15-24-32dcc

Drillers Log

AEPCO Well No. 1 D-15-24-32DCC

Depth	Thickness	Lithology
5	5	surface soil
112	107	yellow sand, medium
120	8	yellow sand, coarse
160	40	clay and gravel
177	17	clay
210	33	clay and gravel
246	36	yellow clay
290	44	clay and gravel
430	140	yellow clay
507	77	yellow clay and gravel
529	22	yellow clay
550	21	yellow clay and gravel
575	25	sand and gravel
642	67	clay and gravel
664	22	clay
720	56	clay and gravel
729	9	clay and gravel, cemented
816	87	clay and gravel
830	14	clay
917	87	clay and gravel
945	28	clay and coarse gravel
955	10	clay and gravel
962	7	clay
985	23	clay, medium sand, and gravel
1030	45	clay and gravel
1117	87	clay

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